



# On the Application of Genetic Algorithms for Optimization of RTM Process Parameters

by Bruce K. Fink, Roopesh Mathur,  
and Suresh G. Advani

ARL-TR-2317

September 2000

Approved for public release; distribution is unlimited.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

---

## Abstract

---

Resin infusion processes are finding increasing applications in the manufacture of composite parts that have geometric and material complexities. In such cases, the placement of gates and vents is nonintuitive and may require expensive repetitive experimentation. Finite element-based resin-flow simulation codes have been successfully used for modeling and analysis of the mold-filling process. Such filling simulations, when coupled with a search algorithm, can also prove useful for optimal design of the filling process. Genetic algorithms (GAs) mimic natural selection and can efficiently “evolve” near-global optimal solutions from a large number of alternative solutions. In this paper, GAs are used to optimize gate and vent locations for the resin-transfer molding (RTM) process in order to minimize fill times and dry-spot formation. A process performance index, or cost function, is defined, which incorporates the fill time and dry-spot formation as primary variables. A part having material and geometric complexities was chosen for a case study. GA and mold-filling simulations were used interactively to search for optimal gate and vent locations to locate near-optimal solutions. The GA was able to find good solutions using less than 1% of simulations of the possible permutations of gates and vents. The case study was also repeated in the presence of racetracking channels. Again, the optimal locations were found by the GA using less than 1% of all possible combinations.

## **Acknowledgment**

The authors gratefully acknowledge the help of Dr. Murat Sozer from the University of Delaware in writing the LBASIC scripts for this work and for his many helpful discussions.

INTENTIONALLY LEFT BLANK.

# Table of Contents

	<u>Page</u>
<b>Acknowledgment .....</b>	iii
<b>List of Figures .....</b>	vii
<b>1. Introduction .....</b>	1
<b>2. Background.....</b>	3
<b>3. Optimal Design and GAs .....</b>	5
3.1 Optimization of Design .....	5
3.2 SGA Procedure.....	7
3.3 Application of SGA to Gate and Vent Location Optimization .....	10
3.4 Optimization With Racetracking Effects .....	13
<b>4. Results .....</b>	13
<b>5. Racetracking Study .....</b>	16
<b>6. Discussion .....</b>	19
6.1 Racetracking Case .....	20
6.2 Resin Waste Through Vent .....	20
<b>7. Further Refinement: Finding Global Optima .....</b>	21
<b>8. Conclusions .....</b>	22
<b>9. References .....</b>	25
<b>Distribution List .....</b>	27
<b>Report Documentation Page.....</b>	47

INTENTIONALLY LEFT BLANK.

## List of Figures

<u>Figure</u>	<u>Page</u>
1. Processing Steps in RTM .....	2
2. Schematic of Optimal Design for the RTM Process .....	6
3. A Function With Multiple Peaks: A Gradient-Based Method is Likely to Find the Local Peak at Point A, While a GA Will Settle on Point B, Near the Global Maximum.....	7
4. Schematic of LIMS-Based Optimization Using GAs .....	8
5. Reproduction, Crossover, and Mutation Operators in GAs .....	9
6. Planar Approximation of the Bed of a Vehicle or Trailer Used for Optimization ....	11
7. Plot of Cost Function With Generation Number for Each Case .....	14
8. Optimal Gate and Vent Placement for Each Case.....	15
9. Plot of Cost Function With Generation Number for Racetracking Study.....	17
10. Optimal Gate and Vent Placement for Racetracking Study With Two Gates and One Vent.....	18
11. Flow-Front Locations With the Optimal Gate and Vent Locations for the Racetracking Case Optimized by the GA.....	19
12. Improved Optima for the Placement of Gates and Vents.....	23



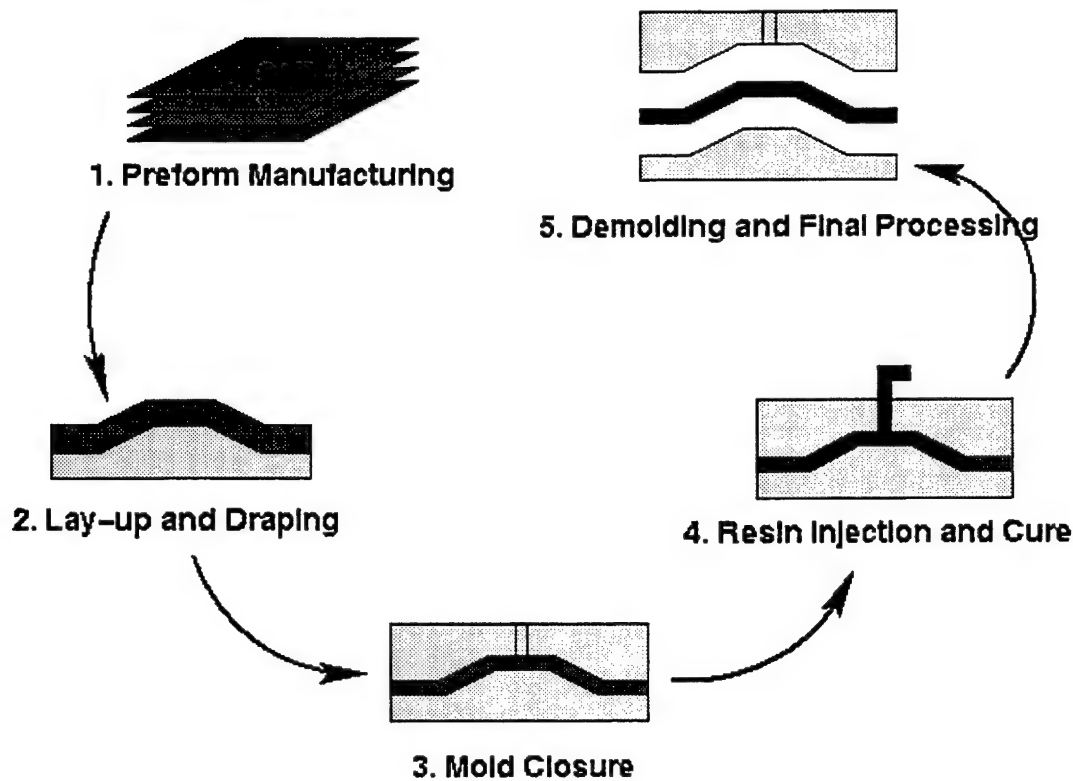
INTENTIONALLY LEFT BLANK.

# 1. Introduction

Liquid-injection molding processes, such as resin-transfer molding (RTM), are being used in the manufacture of composite structures that have varying material properties in aerospace and defense applications. These processes are attractive, since they enable the manufacture of parts with good strength-to-weight ratio, with material properties tailored to specifications, and in desired “net” shapes.

In RTM, the reinforcement material or “preform” is placed inside a mold. The mold is closed, and the resin is injected into it at high pressure through inlet ports or “gates.” Outlet ports or “vents” are used to enable the displaced air to escape out of the mold. The resin impregnates the preform and polymerizes to form the solid part, which is then demolded, as shown in Figure 1 [1]. The manufacture of these complex composite structures by RTM may lead to the problem of “dry spots,” which are areas not wetted-out by the resin due to the trapping of air pockets between flow fronts, thus affecting the quality of the manufactured parts. Mold-filling simulations can track the flow-front location during the impregnation of the preform, once the user has specified the locations of inlet gates and vents. However, there are as many choices for gate and vent locations as there are nodes in the finite element (FE) mesh for the mold geometry. To find the globally optimal locations, one would have to run a large number of simulations. This number could be reduced if an appropriate optimization technique were used. Optimization of the filling process is critical, due to the need to decrease the process cycle time and to complete the filling before the resin starts to cure.

For parts having material and geometric complexities, the location of gates and vents is nonintuitive and extensive trial and error is involved in optimizing their position. Hence, there is a need for a systematic search method that can be interactively coupled with filling simulation capabilities to determine optimally placed gates and vents in order to minimize fill times, as well as dry-spot formation. Of the search techniques studied, genetic algorithms (GAs) have been proven as powerful and robust search methods in dealing with highly nonlinear and large spaces



**Figure 1. Processing Steps in RTM.**

having many possible local optima. In this case, the search space consists of a large number of nodes from FE models and, hence, the number of possibilities is formidable. In addition, with respect to the location of gates and vents, the trends in dry-spot formation and fill time are nonlinear. Hence, GAs were selected as a search method.

In the following sections, some of the pertinent body of work on modeling and simulation of RTM, GAs, and model-based optimization and its application to RTM is reviewed. A description of the operation of a simple genetic algorithm (SGA) is given. The implementation of the SGA with the help of a case study is described, and the results are presented and discussed. It was found that GAs could efficiently locate near optimal gate and vent locations for the manufacture of complex composite parts by RTM, where the optimal locations are not obvious to the designer. The near-optimal gate locations are then used as a starting point to converge onto a globally optimal gate location.

## 2. Background

The flow of resin in porous media is governed by Darcy's Law, which states that the velocity of a fluid flowing through a porous medium is directly proportional to the driving pressure drop:

$$\vec{u} = -\frac{\underline{\underline{K}}}{\eta} \vec{\nabla} P, \quad (1)$$

where  $\vec{u}$  is the average velocity,  $\vec{\nabla} P$  is the pressure gradient in the fluid,  $\underline{\underline{K}}$  is a second rank permeability tensor, and  $\eta$  is the viscosity of the resin. This can be coupled with the continuity equation for incompressible flow (equation [2]) to give a Laplace equation (equation [3]) for the pressure field inside a fibrous porous media permeated by the fluid:

$$\vec{\nabla} \bullet \vec{u} = 0, \quad (2)$$

and

$$\vec{\nabla} \bullet \left( \frac{\underline{\underline{K}}}{\eta} \vec{\nabla} P \right) = 0. \quad (3)$$

This equation can be discretized using FE methods that can be used for simulation of the filling of molds in RTM processes [2–5].

The flow of resin in RTM has been modeled by the discretization of the governing partial differential equation (i.e., equation [3]) using the FE method [2, 3]. The solution involves tracking a moving boundary either using control-volume techniques [4–6] or the movement of a saturation field [7, 8]. Simulation software, such as Liquid-Injection Molding Simulation (LIMS), Version 4.0 [4, 9], uses control volume techniques to simulate the resin flow in

two-dimensional (2-D) molds and in thin three-dimensional (3-D) parts. One may also use the saturation field approach for 2-D or 3-D mold filling. However, the central processing unit (CPU) time is extremely large for 3-D mold filling [10]. Nevertheless, the codes essentially capture the physics of the process. In addition, LIMS can be used to investigate phenomena such as racetracking effects (preferential flow along edges of a mold) and to test control schemes for mold filling [11].

Usually, the geometry; material parameters; gate and vent positions; and pressure or the flow rate, or a combination of the two, are specified before the filling simulation is carried out. The simulation code is used to track the location of the flow fronts, estimate fill times, and account for racetracking effects. In addition, LIMS is capable of showing dry-spot formation and tracking of dry spots as filling progresses [11]. Such flow simulations have also been used to study the effects of different configurations of gates and vents on mold filling, wherein the process inputs are already fixed.

During the filling process, the area of the preform that is poorly wetted-out, or not wetted at all, by the resin, is called a dry spot. Dry spots have been investigated and classified both experimentally and numerically [12, 13]. It has been shown that the positioning and control of gates and vents can lead to dry-spot reduction [11].

The optimal placement of gates and vents and cure-cycle optimization have been carried out using GAs [14, 15]. The method employed used a cost function that is comprised of the maximum difference in times at which the resin reaches the boundary of the mold. This was a measure of the uniformity of filling and, indirectly, of dry-spot formation. However, frequently, the inlets or “gates” are to be located on the edges of the mold and this cost function cannot be used since the resin is injected at the edges. In addition, the locations of gates and vents are dependent on each other in a complex and nonlinear fashion. The present study explicitly defines gate and vent locations and formulates a cost function that accounts for the size of the dry spot and the fill time. These are coupled with the GA and the filling simulation to carry out the optimization of gate and vent locations.

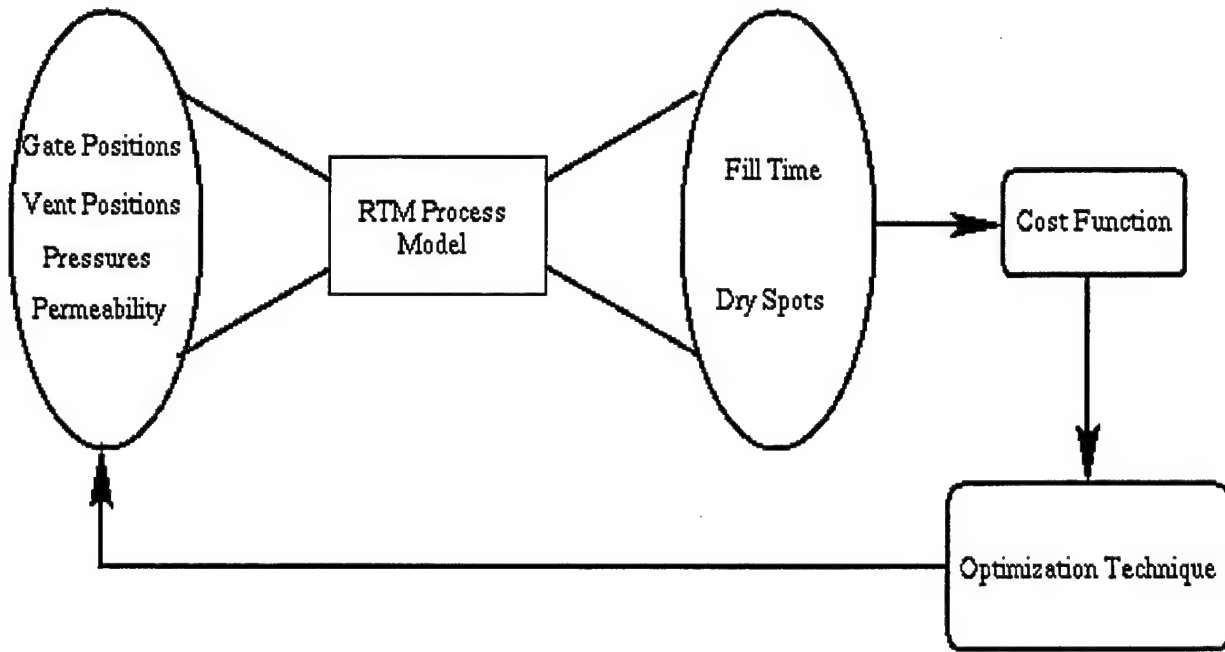
### 3. Optimal Design and GAs

**3.1 Optimization of Design.** Optimal design can be defined as the selection of the best set of inputs for a process to meet certain requirements using available resources. Design optimization proceeds in the following phases: recognition of needs and requirements (problem definition), creation of one or more design configurations (synthesis), the study of the configurations' performance using engineering science and knowledge (analysis), and the selection of the "best" alternative (optimization). The design is defined as a system of design variables, parameters, and constants. The optimal design is selected using a criterion that is called an objective function. The objective function is sometimes referred to as a cost function since a minimum cost is often desired [16].

The selection of an optimal design is usually an iterative process involving a search technique that searches for the "best" design configuration. A mathematical model of the system is used for evaluation of the objective function for each design configuration. The mathematical, or simulation-based, model is a numerical representation of the relationship between process inputs and process outputs. For example, the filling simulation is a very sophisticated model that relates the inputs (e.g., gate and vent positions, permeability data, injection pressures, etc.) to the outputs, such as fill times, pressure fields, and dry-spot formation and location.

As illustrated in Figure 2, the process of optimal design for RTM involves the coupling of a cost function, which incorporates the important criteria for optimal design with a filling simulation. The variables to be optimized are gate and vent positions in order to minimize the fill times and area dry-spot formation.

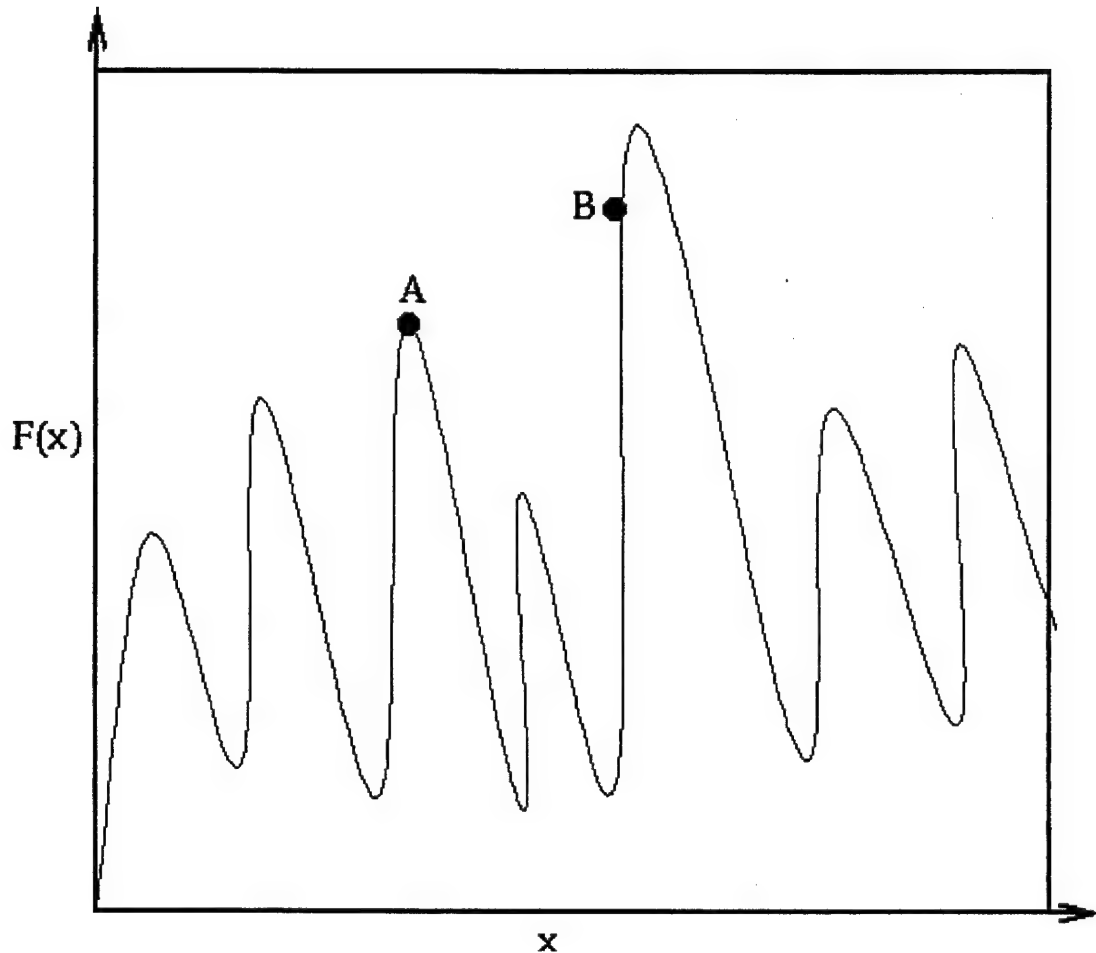
Conventional search techniques are gradient-based. The gradient of the objective function with respect to the design variables is evaluated, and the variables are adjusted along the line of maximum slope until a minimum is reached, where the gradient is zero. Gradient-descent-based techniques tend to get trapped in local minima and strongly depend on an initial guess and on the existence of derivatives.



**Figure 2. Schematic of Optimal Design for the RTM Process.**

GAs are search algorithms that mimic natural selection and genetics to “evolve” the best solution to a problem from a large number of alternative solutions. The solution is usually represented by a binary string. A sample set of solutions, or a “generation,” as represented by their strings is evaluated and fitness values are assigned. Two of the strings are selected at a time and “reproduced” using crossover and mutation operators that are defined mathematically, and they produce two new strings or “offspring,” until a new set of strings or a new generation is produced. The probability of selection is proportional to the fitness of the string. Hence, the “fittest” strings have a greater chance to contribute to the next generation, imitating Darwinian evolution. The next generation is again evaluated and reproduces. The cycle is repeated until a generation having many good solutions emerges [17].

GAs have proven to be robust and powerful techniques for search and optimization. GAs search from a population of points and use payoff or fitness information with probabilistic transition rules. They generally produce near-global optimal solutions in large search spaces. As illustrated in Figure 3, for a multimodal function (i.e., a function possessing multiple peaks) a gradient-based search method will probably settle on a lower peak (i.e., a local optimum), while



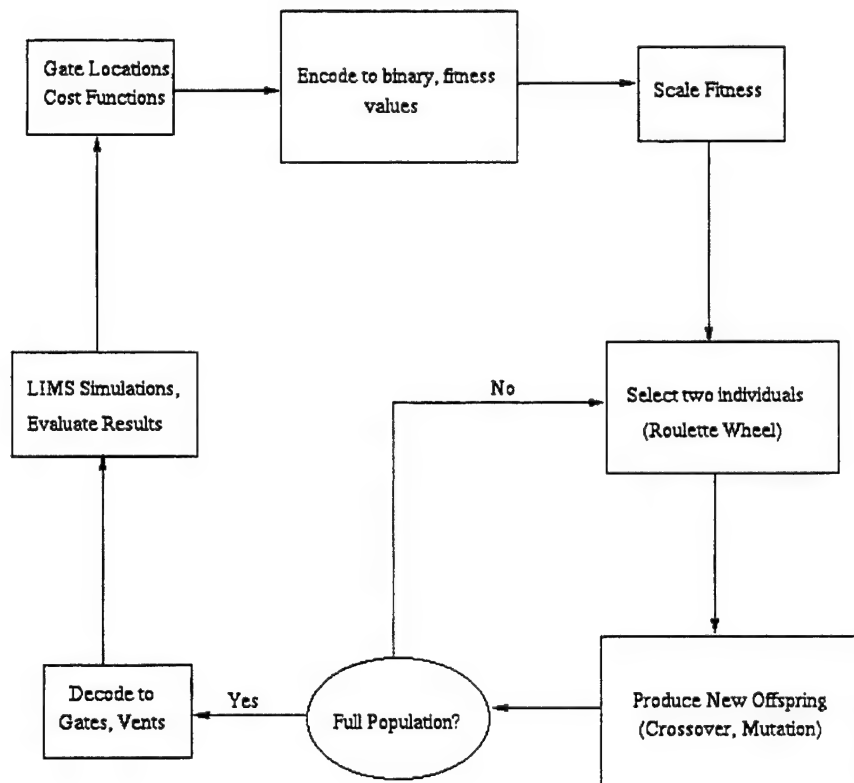
**Figure 3. A Function With Multiple Peaks: A Gradient-Based Method Is Likely to Find the Local Peak at Point A, While a GA Will Settle on Point B, Near the Global Maximum.**

a GA is most likely to find a point close to the absolute maximum. This is because GAs use information from multiple points in parallel to explore the search space. An SGA has been implemented in this work [18].

**3.2 SGA Procedure.** The SGA is a powerful yet simple search technique that involves partial swapping and copying of binary strings, which are representations of the optimization variables. The variables themselves can be continuous or discrete, since they are mapped to binary strings. Each string has a “fitness” value,  $f$ , associated with it. The SGA employs three operators: reproduction, crossover, and mutation.



The reproduction operator operates on the strings of each generation to produce the strings of the next generation. The strings are allocated space on a roulette wheel, with the size of the sector assigned to each string on the circle, being proportional to its fitness. Thus, the roulette wheel is biased in favor of the “fittest” members of each generation. The wheel is spun, and strings are selected two at a time. These two strings are operated on, by the crossover and mutation operators, to produce two new strings, which belong to the next generation. New strings are produced until the population size (i.e., the number of strings in each generation, which is a fixed number) is attained. This new generation is evaluated, and fitness values are assigned to each member of the generation. A schematic of this process is shown in Figure 4.

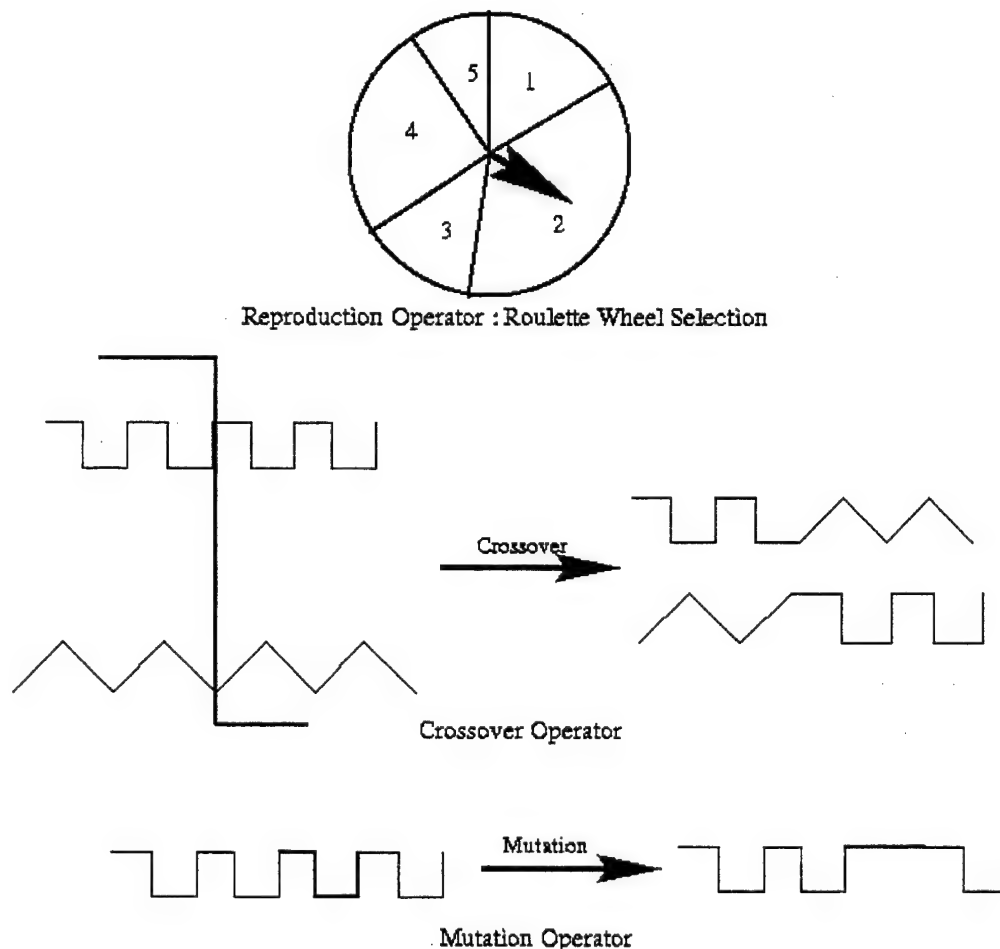


**Figure 4. Schematic of LIMS-Based Optimization Using GAs.**

The crossover operator takes each pair of strings selected by the reproduction operator to produce two new strings. It does this by randomly selecting an integer position on the string, dividing each of the strings at that position, and then swapping the substrings. If the strings (S1

and  $S_2$ ) are each of length  $L$ , a position  $k < L$  is selected and the two strings are divided into four substrings, two of length  $k$  ( $s_1$  and  $s_2$ ) and two of length  $L-k$  ( $r_1$  and  $r_2$ ). The two new strings are  $s_1-r_2$  and  $s_2-r_1$ .

The reproduction and crossover operators work in tandem to use high performance strings having high fitness values and generate better strings having higher fitness values, thus emulating natural selection, which favors "survival of the fittest." The mutation operator works by taking the new strings produced and randomly flipping over a few digits from 0 to 1 or 1 to 0. This ensures genetic diversity by producing strings that contain new material and are not totally derived from the previous generation. The three operators are illustrated in Figure 5.



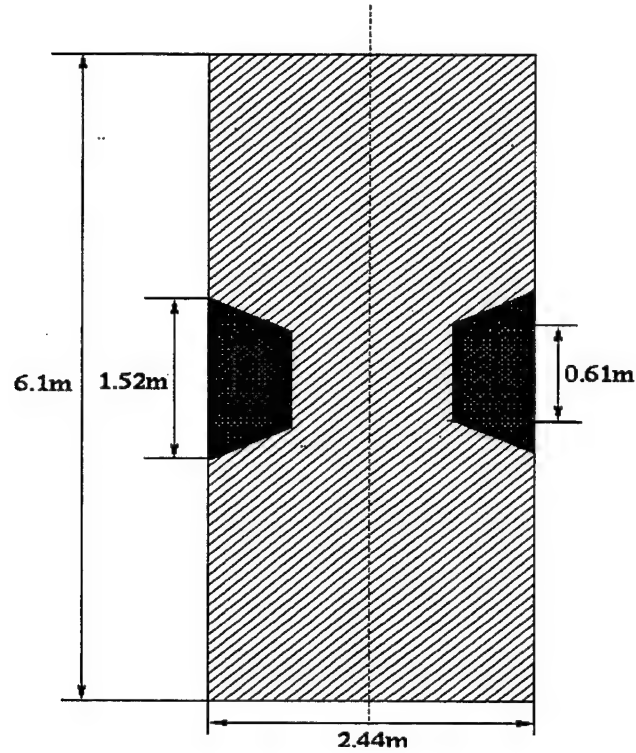
**Figure 5. Reproduction, Crossover, and Mutation Operators in GAs.**

In terms of optimization and search, the SGA works by searching from multiple points in the search space. It is a random-search technique possessing some degree of determinism. This ensures that the algorithm does not get trapped in local optima. The mutation operator ensures that the search is not localized to a small part of the search space. Since there are no requirements on the fitness function, it allows a high degree of freedom in constructing the function. It has been shown that the SGA will usually locate near-global optima in the search space [18].

**3.3 Application of SGA to Gate and Vent Location Optimization.** To illustrate the potential and use of GAs, a composite part having material and geometric complexity was used for the case study. This part is a 2-D approximation of a vehicle bed with wheel wells. It is a large planar part and contains a thick section that provides a path of high resistance to the resin. The search space of possible gate and vent locations was defined. An objective function or process performance index (PPI) was formulated, which incorporates the fill time and dry-spot formation, with appropriate normalized weighting factors.

LIMS 4.0 [11] incorporates the LBASIC script language. A script was written to simulate the filling process with sets of gates and vents arranged in a sequential manner and that abandon the filling simulation when a tolerance on the fill time and dry-spot area is exceeded. Initially, a random set of configurations is evaluated using LIMS and the objective function. The SGA, coded in C++, was then used to generate successive sets or “generations” of configurations, with the LIMS-based simulations supplying the cost information for each set. It was observed that the average costs for successive generations showed a decrease, and several optimal configurations were obtained.

The optimization problem solved here, is that of finding optimal gate and vent locations to minimize fill time and dry spot formed for the selected mold geometry and material parameters (Figure 6). The composite part has thicker sections at the center corresponding to the wheel wells. The permeabilities of the preform material are  $K_{11} = K_{22} = 10^{-7} \text{m}^2$  for the thin section and two orders of magnitude lower,  $K_{11} = K_{22} = 10^{-9} \text{m}^2$ , for the thick section.



**Figure 6. Planar Approximation of the Bed of a Vehicle or Trailer Used for Optimization.**

The injection at the gate is performed under constant pressure, which was chosen to be 10 atm at each gate (i.e., a standard injection pressure for RTM of vinyl-ester resins). The vents are at atmospheric pressure. The resin viscosity was chosen to be 0.231 Pa-s, which is a typical value for vinyl-ester resin. The mold geometry was discretized using the PATRAN FE preprocessor [19].

The optimality criterion was represented by the following objective function that is to be minimized:

$$J = \lambda_1 \frac{t_f(1 + 99H(t - t_{f,tol}))}{t_{f,max}} + \lambda_2 \frac{\%Void(1 + 99H(\%Void - \%Void_{tol}))}{\%Void_{max}}. \quad (4)$$

The PPI formulated incorporated the importance of fill time and voids, although one may include other outputs if necessary. Voids or dry spots are represented by the number of unfilled nodes in the FE model at the end of the simulation. The functions  $H(t - t_{f,tol})$  and

$H(\%Void - \%Void_{tol})$  are Heaviside penalty functions, which add a penalty if tolerance limits on time and void formation are exceeded. The variables  $\lambda_1$  and  $\lambda_2$  are weighting factors that can be adjusted according to the relative importance of each term. The tolerance time is usually less than the time to initiate gelling and the tolerance on void formation is less than a fraction of a percent for structural applications and a few percent for nonstructural applications.

The optimization problem was attempted for case (a), the ideal case of two gates and vents everywhere (i.e., no vents specified, hence, no dry spots are formed, so the objective function was limited to fill times only); case (b), two gates and one fixed-vent location; and case (c), two gates and four vents. Since the mold geometry has left-right symmetry, the flow in only the left section with one gate specified considered. In case (c), there are two vents in the left section placed symmetrically about the centerline; hence, only one vent needs to be independently specified. The search area was initially restricted to the boundary of the mold, which was divided into 128 parts; as in many cases, the mold is held in a press and it is generally costly to inject from the top or the bottom face. Each gate or vent location corresponds to a node in the FE mesh and is represented by a seven-digit binary number. Hence, the gates in cases (a) and (b) are represented by seven-digit binary strings in the GA. In case (c), the gate and two vents are represented by two seven-digit strings joined together.

The worst case for filling is with one gate at the center of the thick section with fixed vent location. The fill time is 62,979 s with 638 unfilled nodes. It was observed that, in case (b), the fill times in the first generation were distributed with 75% of the cases having fill times below 6,500 s and, in case (c), fill times were below 9,500 s. The values of the weighting factors were  $\lambda_1 = 10$  and  $\lambda_2 = 5$ ; and were chosen so that both terms in the cost function have equal importance.

In each case, an initial population of 6–8 strings was generated randomly. These were decoded to gates and vents and the mold-filling simulations were performed using the LBASIC script. The cost function was evaluated. The GA uses the cost function to calculate the fitness of each string, using the linear scaling function,  $fitness(x) = 1,000 - cost(x)$ , and produces the next

generation, which is decoded and evaluated. This optimization loop was continued for several generations, until the average cost function over each generation was below a preset value.

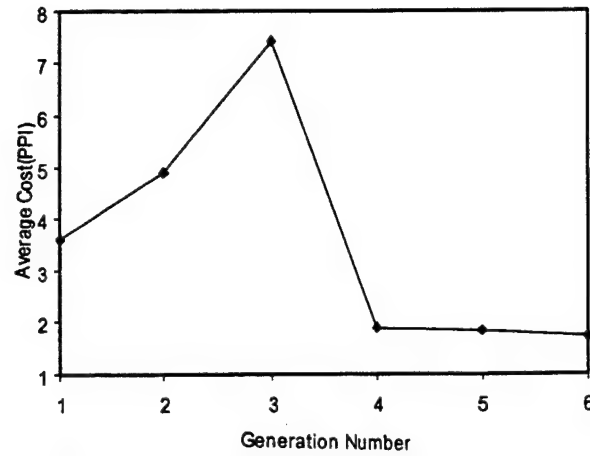
**3.4 Optimization With Racetracking Effects.** Racetracking channels are created when there is a gap between the preform and the mold wall. The channels provide a path of least resistance to the flow and dramatically affect the flow-front movement of the resin in the mold. Thus, the optimal locations of gates and vents to minimize fill time and dry-spot formation, as previously defined, will change.

In the previous study, the boundaries of the mold were considered for the location of gates and vents. In this study, with racetracking effects included, the boundary cannot be the location of both a gate and a vent, since the mold will not fill as the racetracking channel provides a conduit of least resistance from the gate to the vent. However, if one of them were to be located on the mold boundary and the other in the center of the mold, then there exists a possibility for the mold to fill. Hence, for this study, the centerline of the mold was also included in the search space. The geometry on this case study was identical to the previous one, except that a racetracking channel of width 2.54 cm and depth 0.64 cm around the boundary of the mold was incorporated into the FE model of the mold. The total number of possible nodes that could serve as a gate or vent was 304. The optimization problem was solved for the case of two gates placed symmetrically about the centerline of the mold and a single vent placed on the centerline of the mold. Each configuration was represented by a 15-digit binary string, where the first 8 digits correspond to the gate, which can be anywhere on the racetracking channel and the centerline, and the last 7 bits represent the vent, which is restricted to the centerline.

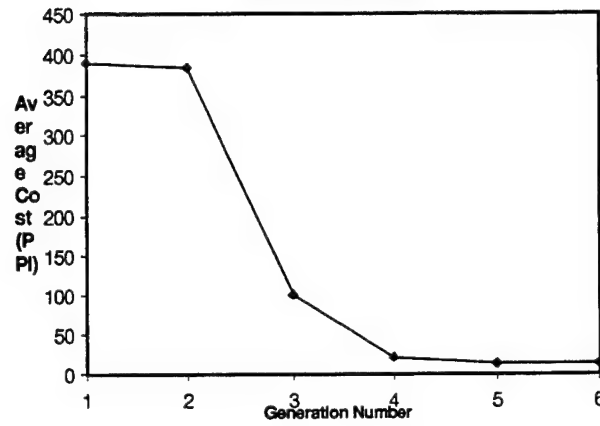
## 4. Results

The GA was first applied for the three cases without the racetracking effect, as described in the previous section, with five to six generations being evolved in each case. The average values of the cost function per generation are plotted in Figure 7. The best configurations are shown for each case in Figure 8.

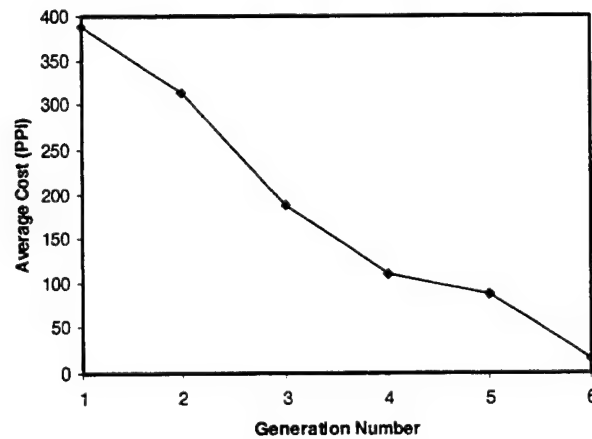
Case (a)



Case (b)

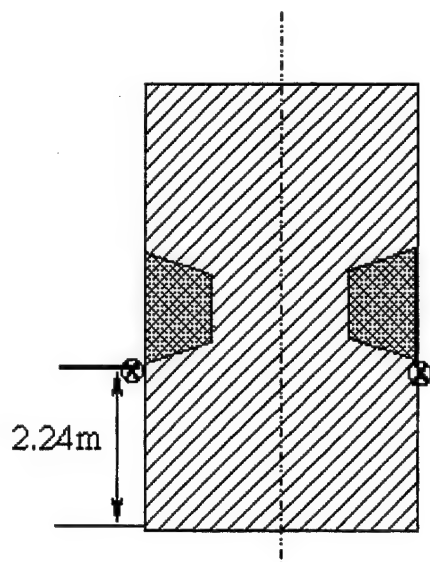


Case (c)

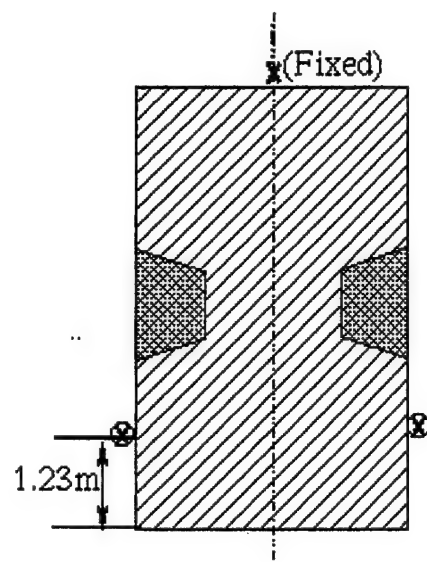


Note: Case (a): Two Gates, Vents Everywhere.  
Case (b): Two Gates, One Fixed Vent.  
Case (c): Two Gates, Four Vents, No Racetracking.

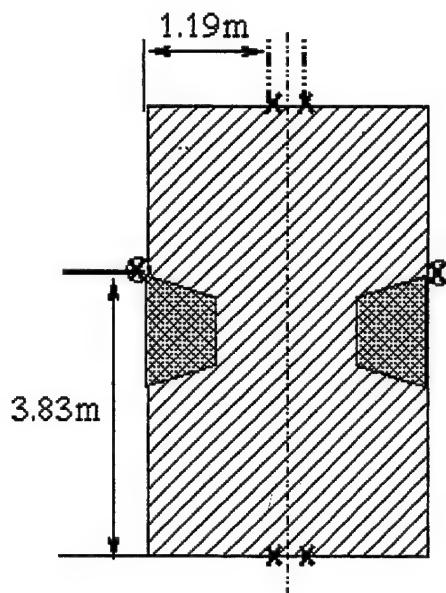
**Figure 7. Plot of Cost Function With Generation Number for Each Case.**



(a)



(b)



(c)

⊗ Gate

⊗ Vent

Note: Case (a): Two Gates, Vent Everywhere, Fill Time = 3,292 s.  
 Case (b): Two Gates, One Fixed Vent, Fill Time = 4,291.6 s.  
 Case (c): Two Gates, Four Vents, Fill Time = 4,407 s.

**Figure 8. Optimal Gate and Vent Placement for Each Case.**



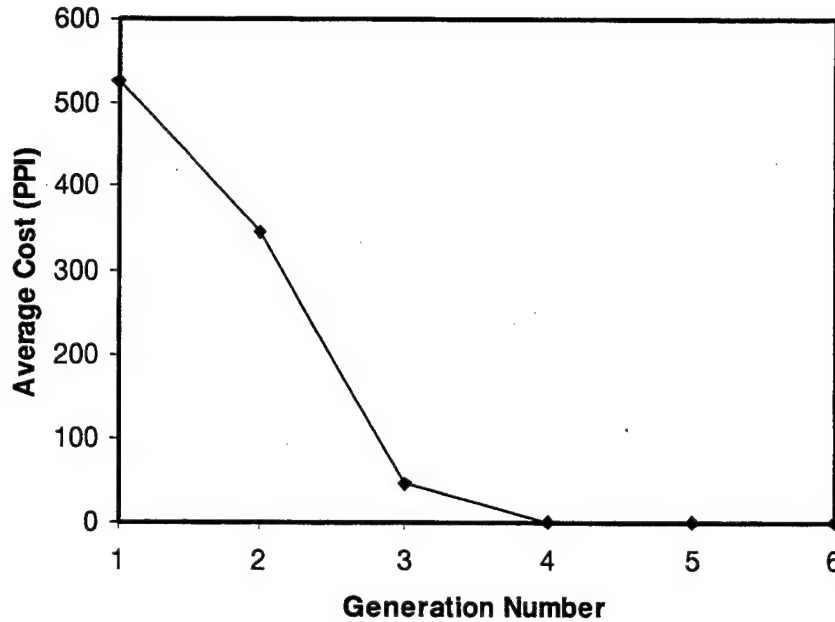
In case (a), when it is assumed that the vent is present everywhere, the average value of the cost function was 3.62 for the first generation and 1.82 for the sixth generation. The best time to fill was 3,290 s, with the gate being located next to the thick section. This makes sense and can be explained as follows: the optimal gate location is as close to the centerline of the part as possible since the resin has to travel the minimum distance. But the thick section is located at the center of the part, and a gate location in the thick section would require a very high time to fill since the flow is at constant pressure and will be forced to go through the high resistance to flow in the thick section. Hence, the optimal gate location is at the edge of the thick section. The number of gates evaluated was 16 out of a possible 32.

In case (b), the gate was allowed to float along the edge of the mold and the vent was fixed at the position shown in Figure 8(b). The average cost value decreased from 390.7 to 12.9 in five generations. The best solution was calculated to take a fill time of 4,292 s and unfilled nodes = 23 or 0.008% dry-spot formation. The number of gates evaluated was 25 out of a possible 128.

In case (c), the vent was free to move in addition to the gate location. The average value of the cost function, as expressed in equation (4), decreased from 388.3 to 14.23 in six generations. The best solution was fill time = 4,407 s, unfilled nodes = 17 or 0.006% dry-spot formation. The number of gate and vent configurations evaluated were 40 out of a possible 16,256 gate and vent configurations. One can see that, as the number of possible configurations increased, the utility of the GA becomes evident, as it was able to locate an optimal solution with fewer than 1% possible evaluations. The vent location was very close to the line of symmetry. A local search showed that the vent should be at the symmetry line, as shown in Figure 8(c).

## 5. Racetracking Study

In the racetracking study, from 83,000 possible configurations, the GA took 6 generations and 48 simulations to arrive at a near-optimal solution. The average cost function decreased with successive generations and is plotted in Figure 9. Two optimal solutions were obtained that minimized the time to fill and low dry-spot formation using just 0.14% of possible evaluations.



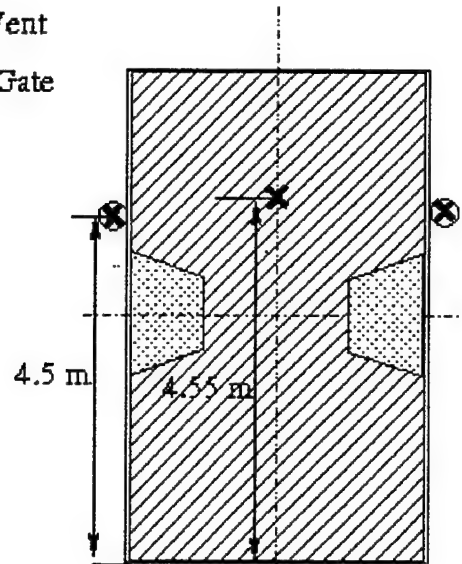
**Figure 9. Plot of Cost Function With Generation Number for Racetracking Study.**

These are shown in Figure 10. The optimal fill times are much less than those in the case without racetracking channels. The flow contours for the best gate and vent configurations are plotted in Figure 11.

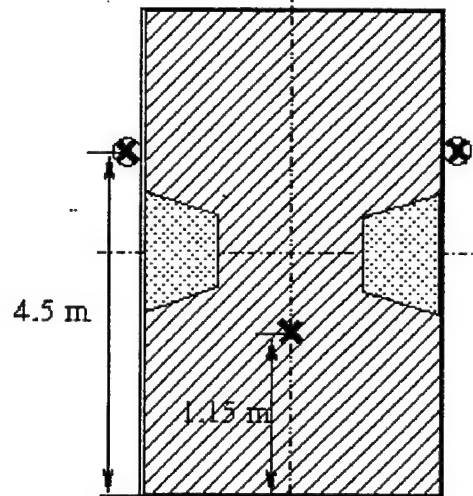
In the previously mentioned case study, the simulation of resin flow in the mold was stopped at a critical time, reflecting the need to complete the mold filling in a finite time, which may be dependent on cycle time requirements, or gel on time of the resin. However, it may be imperative to fill the mold completely in order to obtain good-quality parts. Thus, the resin injection has to be continued for some time until the mold filling is complete. Since the thick section is the last to fill and the vent here is in the thin section, there will be considerable resin wastage through the vent.

The continuous injection was undertaken for the best configuration of two gates and a vent. The mold was filled in 5,309 s (i.e., 20% more time than the 3839.2 s previously considered). The amount of resin wasted through the vent increased to 20% of the total inflow through the gate.

✕ Vent  
 ⊗ Gate



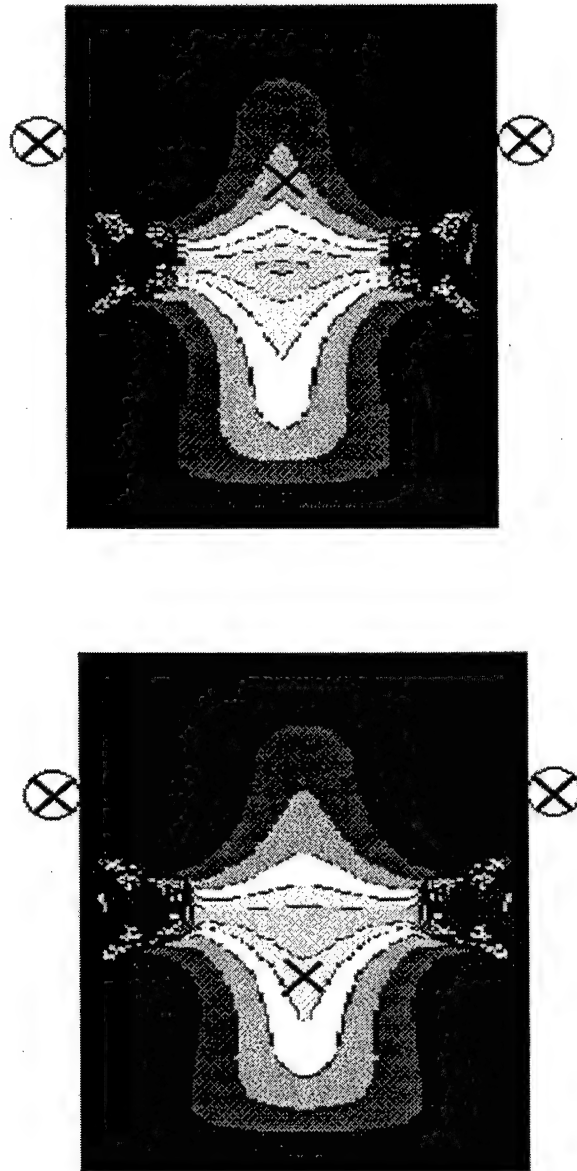
(a)



(b)

Note: Case (a): Fill Time = 3,889.2 s, Dry Spot = 0.7% , Wastage = 6.0%.  
 Case (b): Fill Time = 3,839.2 s, Dry Spot = 0.61%, Wastage = 6.7%.

**Figure 10. Optimal Gate and Vent Placement for Racetracking Study With Two Gates and One Vent.**



**Figure 11. Flow-Front Locations With the Optimal Gate and Vent Locations for the Racetracking Case Optimized by the GA.**

## **6. Discussion**

For the case with no racetracking, when a vent is present in the mold and once the resin reaches the vent, it tends to flow from the gate into the vent, as that is the path of least resistance. Hence, if the vent is in the proximity of the gate, then this path is established quickly and the time to fill will be high due to the leakage of resin through the vent and/or with large dry spots

being formed. Thus, the optimal gate location will involve a trade-off between maximum distance between gates and vents and minimum distance from the centerline. This is reflected in the best gate and vent locations determined by the GA for cases (b) and (c).

It was observed that the average value of the cost function decreased with succeeding generations in each case. A number of possibly optimal solutions for each problem were generated. The number of simulations required before the GA found optimal points was much less than the possible number of simulations.

**6.1 Racetracking Case.** For the case with racetracking, the best gate locations should be placed on the racetracking channel, while the best vent locations should be placed close to the center of the part. This is because the resistance to the flow of resin is the least when it is on the empty racetracking channel. When the gate is on the racetracking channel, it fills quickly, due to low resistance, and acts as a gate. The resin reaches the vent rapidly and then flows through it. This leads to an undesirable quantity of waste resin. Hence, the vent has to be as far away from the racetracking channel as possible. The optimal gate and vent configurations generated by the GA reflect this behavior (Figure 11).

**6.2 Resin Waste Through Vent.** In the present study, it was observed that there is waste due to the flow of resin through the vent. It can also be seen from the flow contours that the last point to fill is in the thick section, due to its low permeability and a very high resistance to flow. The question arises whether a single vent in each of the thick sections will eliminate the waste of resin altogether as this is the last point to fill.

However, a vent is introduced into the mold in order to allow the entrapped air in the mold to escape. In a large and complex mold, there will be many areas where the air can be entrapped. In the mold considered here, air pockets will form not only in the thick section, but also along the centerline, at the intersection of the two flow-fronts. Hence, if the vent on the centerline were to be eliminated, a dry spot would form in the center of the finished part. However, a vent in the thick section is necessary, in any case. An issue that arises is that of minimizing the resin waste. This minimization is implicit here because, if a greater amount of resin were wasted due to the

suboptimal placement of the vent, the fill time would be higher. Hence, the cost function reflects this and the best configurations obtained here have low resin waste (Figure 10).

## **7. Further Refinement: Finding Global Optima**

The GA here has proven adept at finding good configurations of gates and vents to minimize the fill times and areas of dry spots formed. However, the GA is a search technique that has incorporated an element of randomness. This randomness and the fact that it is a multipoint search technique enables one to quickly find points of interest (i.e., good configurations of gates and vents). For this same reason, these configurations are likely not to be global optima (i.e., the absolute minimum) that one could obtain using an exhaustive search through the thousands of possible configurations. Indeed, GAs have been shown to find near-global optima, when applied to well-known optimization problems. Hence, it is likely that the configurations obtained here lie close to global optima (as in Figure 3). The results can be further refined using a local search technique, such as an exhaustive search or a gradient search, and better configurations can be discovered with very little computational cost. In addition, physical insight obtained from the analysis of the gate and vent configurations can be used for further experimentation.

In the case with no racetracking and dealing with the optimal placement of two gates and four vents, the best solution obtained has the gate near the thick section, while the vents are very close to the centerline (Figure 7). Thus, the globally optimal solution would be to have a vent at both ends of the centerline and the gates near the thick section.

In the case with racetracking, it can be seen from the flow contours that the best vent locations are close to the center of the part, while the gate locations are again close to the thick section. Since the racetracking channel is also present there, the gate can be placed on the portion of the racetracking channel near the thick section. Hence, the globally optimal solution will be to have the gate at the center of this portion and the vent at the center of the part. A simulation of this configuration yields a time of 3,555 s to fill 99.4% of the part (i.e., a dry spot occupying 0.6% volume was formed), if the filling is stopped at this point. This optimal configuration is likely to have been found if the cost function severely penalized the resin

wastage. Continuing the filling process, it takes 5,561 s to completely fill the part with 17.1% of the resin wastage. The global optima for both cases (with and without racetracking) are illustrated in Figure 12. Since the points to fill last are always in the thick section, it may also be necessary to have a vent at its center.

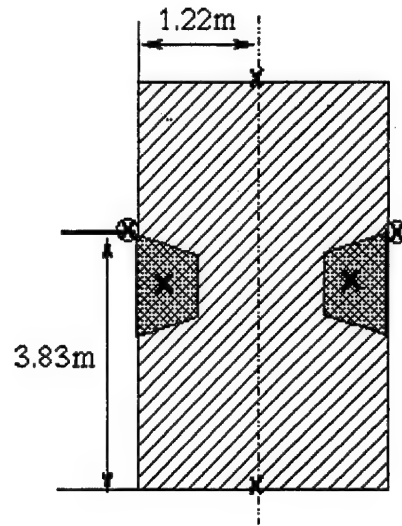
## 8. Conclusions

To determine optimal location of gates and vents, so as to reduce fill times and improve part quality, is a nonlinear problem for the design of molds for RTM, for the manufacture of composite parts with geometric and material complexities. The solution of this problem requires extensive experimentation on a trial-and-error basis.

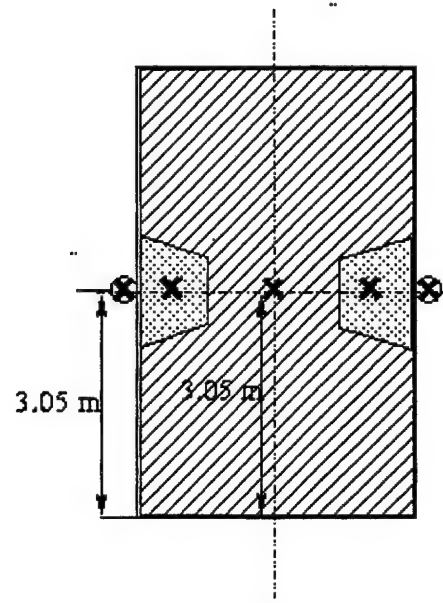
A simple GA coupled interactively with finite-element-based simulations has been used as an effective search technique for determining optimal gate and vent configurations, which minimize fill times and dry-spot formation. A PPI was formulated, which incorporates fill time and dry-spot formation directly, with penalties for exceeding performance tolerances. The case study was extended by adding channels that introduce racetracking effects. The solutions obtained made physical sense and can be easily improved using a local search technique.

The approach used here can be applied to obtain solutions to mold design quickly, where the placement of gates and vents may be nonintuitive. The search space can be restricted to a small part of the mold where the placement of gates and vents is feasible. A cost function can be defined, which reflects the process requirements and penalizes bad performance. A GA is an efficient and practical tool, which can determine good configurations of gates and vents from a large number of possibilities. The analysis was carried out by coupling the GA with our mold-filling simulation software, LIMS. The analysis of these configurations and the improvement of the solutions yields valuable insight into the placement of gates and vents in the mold. This would reduce expensive mistakes during the manufacturing of the composite part.

✕ Vent  
⊗ Gate



(a)



(b)

Note: (a) No Racetracking Channel, Fill Time = 4,407 s, Dry Spot = 0.006%.

(b) Racetracking Channel Incorporated, Fill Time = 3,555 s, Dry Spot = 0.6%.

**Figure 12. Improved Optima for the Placement of Gates and Vents.**



INTENTIONALLY LEFT BLANK.

## 9. References

1. Fong, L., and S. G. Advani. *Lubin's Handbook of Composites II*. S. T. Peters (editor), 1998.
2. Bruschke, M. V., and S. G. Advani. "RTM: Filling Simulation of Complex Three-Dimensional Shell-Like Structures." *SAMPE Quarterly*, pp. 2-11, 1991.
3. Lee, L. J., W. B. Young, and R. J. Lin. "Mold Filling and Cure Modeling of RTM and SRIM Processes." *Composite Structures*, vol. 27, no. 1-2, 1994.
4. Trochu, F., R. Gauvin, D. M. Gao, and J. F. Boudreault. "RTMFLOT - An Integrated Software Environment for the Computer Simulation of the Resin Transfer Molding Process." *Journal of Reinforced Plastics and Ceramics*, vol. 13, no. 3, 1994.
5. Bruschke, M. V., and S. G. Advani. "A Numerical Approach to Model Non-Isothermal, Viscous Flow With Free Surfaces Through Fibrous Media." *International Journal of Numerical Methods in Fluids*, vol. 19, pp. 575-603, 1991.
6. Bruschke, M. V., and S. G. Advani. "A Finite Element/Control Volume Approach to Mold Filling in Anisotropic Porous Media." *Polymer Composites*, vol. 11, pp. 398-405, 1990.
7. Gallez, X. E., and S. G. Advani. "Numerical Simulations for Impregnation of Fiber Preforms in Composites Manufacturing." *Proceedings of the Fourth International Conference on Flow Processes in Composite Materials*, University of Wales, 1996.
8. Mohan, R. V., N. D. Ngo, K. K. Tamma, and K. D. Fickie. "On a Pure Finite Element Based Methodology for Resin Transfer Mold Filling Simulations." *Numerical Methods in Thermal Problems, Proceedings of the Ninth International Conference*, Part 2, 1995.
9. Advani, S. G. "Numerical Issues and Approaches in Simulation of VARTM Processes." *Proceedings of the ASME Annual Winter Meeting*, Dallas, TX, 1997.
10. Simacek, P., E. M. Sozer, and S. G. Advani. *User Manual for DRAPE 1.1 and LIMS 4.0*. University of Delaware Center for Composite Materials, 1998.
11. Liu, D., S. Bickerton, and S. G. Advani. "Modeling and Simulation of RTM: Gate Control, Venting and Dry Spot Prediction." *Composites*, vol. 27A, no. 135, 1996.
12. Han, K., and L. K. Lee. "Dry Spot Formation and Changes in Liquid Composite Molding: I-Experimental." *Journal of Composite Materials*, vol. 30, no. 13, 1996.

13. Han K., L. K. Lee, and S. Nakamura. "Dry Spot Formation and Changes in Liquid Composite Molding: II-Modeling and Simulation." *Journal of Composite Materials*, vol. 30, no. 13, 1996.
14. Young W. B. "Gate Location Optimization in Liquid Composite Molding Using Genetic Algorithms." *Journal of Composite Materials*, vol. 28, no. 12, 1994.
15. Young, W. B., and W. H. Yu. "Optimal Design of Process Parameters for Resin Transfer Molding." *Journal of Composite Materials*, vol. 31, no. 11, 1997.
16. Papalambros, P. Y., and D. E. Wilde. *Principles of Optimal Design: Modeling and Computation*. Cambridge University Press, 1988.
17. Mitchell, M. E. *An Introduction to Genetic Algorithms*. MIT Press, 1996.
18. Goldberg, D. E. *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley, 1997.
19. PDA Engineering: PATRAN Division. *PATRAN Users Manual: Version 5*. PDA, 1997.

NO. OF  
COPIES   ORGANIZATION

2   DEFENSE TECHNICAL  
INFORMATION CENTER  
DTIC DDA  
8725 JOHN J KINGMAN RD  
STE 0944  
FT BELVOIR VA 22060-6218

1   HQDA  
DAMO FDT  
400 ARMY PENTAGON  
WASHINGTON DC 20310-0460

1   OSD  
OUSD(A&T)/ODDDR&E(R)  
R J TREW  
THE PENTAGON  
WASHINGTON DC 20301-7100

1   DPTY CG FOR RDA  
US ARMY MATERIEL CMD  
AMCRDA  
5001 EISENHOWER AVE  
ALEXANDRIA VA 22333-0001

1   INST FOR ADVNCD TCHNLGY  
THE UNIV OF TEXAS AT AUSTIN  
PO BOX 202797  
AUSTIN TX 78720-2797

1   DARPA  
B KASPAR  
3701 N FAIRFAX DR  
ARLINGTON VA 22203-1714

1   NAVAL SURFACE WARFARE CTR  
CODE B07 J PENNELLA  
17320 DAHLGREN RD  
BLDG 1470 RM 1101  
DAHLGREN VA 22448-5100

1   US MILITARY ACADEMY  
MATH SCI CTR OF EXCELLENCE  
MADN MATH  
MAJ HUBER  
THAYER HALL  
WEST POINT NY 10996-1786

NO. OF  
COPIES   ORGANIZATION

1   DIRECTOR  
US ARMY RESEARCH LAB  
AMSRL D  
D R SMITH  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

1   DIRECTOR  
US ARMY RESEARCH LAB  
AMSRL DD  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

1   DIRECTOR  
US ARMY RESEARCH LAB  
AMSRL CI AI R (RECORDS MGMT)  
2800 POWDER MILL RD  
ADELPHI MD 20783-1145

3   DIRECTOR  
US ARMY RESEARCH LAB  
AMSRL CI LL  
2800 POWDER MILL RD  
ADELPHI MD 20783-1145

1   DIRECTOR  
US ARMY RESEARCH LAB  
AMSRL CI AP  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

4   DIR USARL  
AMSRL CI LP (BLDG 305)

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	HQDA DAMI FIT NOLAN BLDG WASHINGTON DC 20310-1025
1	DIRECTOR DA OASARDA SARD SO 103 ARMY PENTAGON WASHINGTON DC 20310-0103
1	DPTY ASST SECY FOR R&T SARD TT THE PENTAGON RM 3EA79 WASHINGTON DC 20301-7100
1	COMMANDER US ARMY MATERIEL CMD AMXMI INT 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	COMMANDER US ARMY ARDEC AMSTA AR AE WW E BAKER J PEARSON PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR TD C SPINELLI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSE PICATINNY ARSENAL NJ 07806-5000
6	COMMANDER US ARMY ARDEC AMSTA AR CCH A W ANDREWS S MUSALLI R CARR M LUCIANO E LOGSDEN T LOUZEIRO PICATINNY ARSENAL NJ 07806-5000
4	COMMANDER US ARMY ARDEC AMSTA AR CC G PAYNE J GEHBAUER C BAULIEU H OPAT PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T C C PATEL PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA F DIORIO PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSP A P KISATSKY PICATINNY ARSENAL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
9	COMMANDER US ARMY ARDEC AMSTA AR CCH B P DONADIA F DONLON P VALENTI C KNUTSON G EUSTICE S PATEL G WAGNECZ R SAYER F CHANG PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR CCH C H CHANIN S CHICO PICATINNY ARSENAL NJ 07806-5000
6	COMMANDER US ARMY ARDEC AMSTA AR CCL F PUZYCKI R MCHUGH D CONWAY E JAROSZEWSKI R SCHLENNER M CLUNE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR SRE D YEE PICATINNY ARSENAL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY ARDEC AMSTA AR WET T SACHAR BLDG 172 PICATINNY ARSENAL NJ 07806-5000	6	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE R KOWALSKI W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA ASF PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY ARDEC PRDCTION BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC INTELLIGENCE SPECIALIST AMSTA AR WEL F M GUERRIERE PICATINNY ARSENAL NJ 07806-5000	3	COMMANDER US ARMY TACOM PM TACTICAL VEHICLES SFAE TVL SFAE TVM SFAE TVH 6501 ELEVEN MILE RD WARREN MI 48397-5000
11	PM TMAS SFAE GSSC TMA R MORRIS C KIMKER D GUZOWICZ E KOPACZ R ROESER R DARCY R MCDANOLDS L D ULISSE C ROLLER J MCGREEN B PATTEN PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY TACOM PM BFVS SFAE ASM BV 6501 ELEVEN MILE RD WARREN MI 48397-5000
2	PEO FIELD ARTILLERY SYS SFAE FAS PM H GOLDMAN T MCWILLIAMS PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY TACOM PM AFAS SFAE ASM AF 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM ABRAMS SFAE ASM AB 6501 ELEVEN MILE RD WARREN MI 48397-5000	1	COMMANDER US ARMY TACOM PM RDT&E SFAE GCSS W AB J GODELL 6501 ELEVEN MILE RD WARREN MI 48397-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	<p>COMMANDER US ARMY TACOM PM SURV SYS SFAE ASM SS T DEAN SFAE GCSS W GSI M D COCHRAN 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM PM SURVIVABLE SYSTEMS SFAE GCSS W GSI H M RYZYI 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM PM BFV SFAE GCSS W BV S DAVIS 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM PM LIGHT TACTICAL VHCLS AMSTA TR S A J MILLS MS 209 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM PM GROUND SYSTEMS INTEGRATION SFAE GCSS W GSI R LABATILLE 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM CHIEF ABRAMS TESTING SFAE GCSS W AB QT T KRASKIEWICZ 6501 ELEVEN MILE RD WARREN MI 48397-5000</p>

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
14	<p>COMMANDER US ARMY TACOM AMSTA TR R J CHAPIN R MCCLELLAND D THOMAS J BENNETT D HANSEN AMSTA JSK S GOODMAN J FLORENCE K IYER J THOMSON AMSTA TR D D OSTBERG L HINOJOSA B RAJU AMSTA CS SF H HUTCHINSON F SCHWARZ WARREN MI 48397-5000</p>
1	<p>COMMANDER US ARMY TACOM AMSTA SF WARREN MI 48397-5000</p>
1	<p>COMMANDER WATERVLIET ARSENAL SMCWV QAE Q B VANINA BLDG 44 WATERVLIET NY 12189-4050</p>
1	<p>COMMANDER WATERVLIET ARSENAL SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET NY 12189-4050</p>
2	<p>TSM ABRAMS ATZK TS S JABURG W MEINSHAUSEN FT KNOX KY 40121</p>



<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
10	BENET LABORATORIES AMSTA AR CCB R FISCELLA G D ANDREA M SCAVULO G SPENCER P WHEELER K MINER J VASILAKIS G FRIAR R HASENBEIN AMSTA CCB R S SOPOK WATERVLIET NY 12189-4050
3	ARMOR SCHOOL ATZK TD R BAUEN J BERG A POMEY FT KNOX KY 40121
2	HQ IOC TANK AMMUNITION TEAM AMSIO SMT R CRAWFORD W HARRIS ROCK ISLAND IL 61299-6000
1	DIRECTOR US ARMY AMCOM SFAE AV RAM TV D CALDWELL BLDG 5300 REDSTONE ARSENAL AL 35898
2	COMMANDER US ARMY AMCOM AVIATION APPLIED TECH DIR J SCHUCK FT EUSTIS VA 23604-5577
1	US ARMY CRREL P DUTTA 72 LYME RD HANOVER NH 03755

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
4	DIRECTOR US ARMY CECOM NIGHT VISION & ELECTRONIC SENSORS DIR AMSEL RD NV CM CCD R ADAMS R MCLEAN A YINGST AMSEL RD NV VISP E JACOBS 10221 BURBECK RD FT BELVOIR VA 22060-5806
1	US ARMY CERL R LAMPO 2902 NEWMARK DR CHAMPAIGN IL 61822
2	US ARMY CORPS OF ENGINEERS CERD C T LIU CEW ET T TAN 20 MASS AVE NW WASHINGTON DC 20314
1	US ARMY COLD REGIONS RSCH & ENGRNG LAB P DUTTA 72 LYME RD HANOVER NH 03755
1	SYSTEM MANAGER ABRAMS ATZK TS LTC J H NUNN BLDG 1002 RN 110 FT KNOX KY 40121
1	DIR OF CMBT DEVELOPMENT C KJORO 320 ENGINEER LOOP STE 141 FT LEONARD WOOD MO 65473-8929
1	COMMANDANT US ARMY FIELD ARTILLERY CENTER AT FT SILL ATFS CD LTC BUMGARNER FT SILL OK 73503-5600

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
10	DIRECTOR US ARMY NATIONAL GROUND INTELLIGENCE CTR D LEITER S EITELMAN M HOLTUS M WOLFE S MINGLEDORF H C ARDLEIGH J GASTON W GSTATTENBAUER R WARNER J CRIDER 220 SEVENTH ST NE CHARLOTTESVILLE VA 22091
6	US ARMY SBCCOM SOLDIER SYSTEMS CENTER BALLISTICS TEAM J WARD MARINE CORPS TEAM J MACKIEWICZ BUS AREA ADVOCACY TEAM W HASKELL SSCNC WST W NYKVIST T MERRILL S BEAUDOIN KANSAS ST NATICK MA 01760-5019
9	US ARMY RESEARCH OFC A CROWSON J CHANDRA H EVERETT J PRATER R SINGLETON G ANDERSON D STEPP D KISEROW J CHANG PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	CHIEF USAIC ATZB COM LTC T J CUMMINGS FT BENNING GA 31905-5800

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	NAVAL AIR SYSTEMS CMD J THOMPSON 48142 SHAW RD UNIT 5 PATUXENT RIVER MD 20670
1	NAVAL SURFACE WARFARE CTR DAHLGREN DIV CODE G06 DAHLGREN VA 22448
1	NAVAL SURFACE WARFARE CTR TECH LIBRARY CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
3	NAVAL RESEARCH LAB I WOLOCK CODE 6383 R BADALIANCE CODE 6304 L GAUSE WASHINGTON DC 20375
1	NAVAL SURFACE WARFARE CTR CRANE DIVISION M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
1	COMMANDER NAVAL SURFACE WARFARE CTR CADEROCK DIVISION R PETERSON CODE 2020 M CRITCHFIELD CODE 1730 BETHESDA MD 20084
1	NAVAL SURFACE WARFARE CTR U SORATHIA C WILLIAMS CD 6551 9500 MACARTHUR BLVD WEST BETHESDA MD 20817
1	DAVID TAYLOR RESEARCH CTR SHIP STRUCTURES & PROTECTION DEPT CODE 1702 BETHESDA MD 20084
2	DAVID TAYLOR RESEARCH CTR R ROCKWELL W PHYLLAIER BETHESDA MD 20054-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	OFC OF NAVAL RESEARCH D SIEGEL CODE 351 800 N QUINCY ST ARLINGTON VA 22217-5660	1	AFRL MLBC 2941 P ST RM 136 WRIGHT PATTERSON AFB OH 45433-7750
8	NAVAL SURFACE WARFARE CTR J FRANCIS CODE G30 D WILSON CODE G32 R D COOPER CODE G32 J FRAYSSE CODE G33 E ROWE CODE G33 T DURAN CODE G33 L DE SIMONE CODE G33 R HUBBARD CODE G33 DAHLGREN VA 22448	1	AFRL MLSS R THOMSON 2179 12TH ST RM 122 WRIGHT PATTERSON AFB OH 45433-7718
1	NAVAL SEA SYSTEMS CMD D LIESE 2531 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160	2	AFRL F ABRAMS J BROWN BLDG 653 2977 P ST STE 6 WRIGHT PATTERSON AFB OH 45433-7739
1	NAVAL SURFACE WARFARE CTR M LACY CODE B02 17320 DAHLGREN RD DAHLGREN VA 22448	1	AFRL MLS OL L COULTER 7278 4TH ST BLDG 100 BAY D HILL AFB UT 84056-5205
1	OFC OF NAVAL RES J KELLY 800 NORTH QUINCEY ST ARLINGTON VA 22217-5000	1	OSD JOINT CCD TEST FORCE OSD JCCD R WILLIAMS 3909 HALLS FERRY RD VICKSBURG MS 29180-6199
2	NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R CRANE CODE 2802 C WILLIAMS CODE 6553 3A LEGGETT CIR BETHESDA MD 20054-5000	1	DEFENSE NUCLEAR AGENCY INNOVATIVE CONCEPTS DIV 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
1	NAVSEA OJRI PEO DD21 PMS500 G CAMPONESCHI 2351 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5165	1	WATERWAYS EXPERIMENT D SCOTT 3909 HALLS FERRY RD SC C VICKSBURG MS 39180
1	EXPEDITIONARY WARFARE DIV N85 F SHOUP 2000 NAVY PENTAGON WASHINGTON DC 20350-2000	3	DARPA M VANFOSSSEN S WAX L CHRISTODOULOU 3701 N FAIRFAX DR ARLINGTON VA 22203-1714

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	SERDP PROGRAM OFC PM P2 C PELLERIN B SMITH 901 N STUART ST STE 303 ARLINGTON VA 22203
1	FAA MIL HDBK 17 CHAIR L ILCEWICZ 1601 LIND AVE SW ANM 115N RENTON VA 98055
2	FAA TECH CENTER D OPLINGER AAR 431 P SHYPRYKEVICH AAR 431 ATLANTIC CITY NJ 08405
1	US DEPT OF ENERGY OFC OF ENVIRONMENTAL MANAGEMENT P RITZCOVAN 19901 GERMANTOWN RD GERMANTOWN MD 20874-1928
1	DIRECTOR LLNL F ADDESSI MS B216 PO BOX 1633 LOS ALAMOS NM 87545
5	DIRECTOR LLNL R CHRISTENSEN S DETERESA F MAGNESS M FINGER MS 313 M MURPHY L 282 PO BOX 808 LIVERMORE CA 94550
1	OAK RIDGE NATIONAL LABORATORY R M DAVIS PO BOX 2008 OAK RIDGE TN 37831-6195

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
7	NIST R PARNAS J DUNKERS M VANLANDINGHAM MS 8621 J CHIN MS 8621 D HUNSTON MS 8543 J MARTIN MS 8621 D DUTHINH MS 8611 100 BUREAU DR GAITHERSBURG MD 20899
1	OAK RIDGE NATIONAL LABORATORY C EBERLE MS 8048 PO BOX 2009 OAK RIDGE TN 37831
1	OAK RIDGE NATIONAL LABORATORY C D WARREN MS 8039 PO BOX 2009 OAK RIDGE TN 37922
1	LOCKHEED MARTIN MISSILES & FIRE CONTROL R TAYLOR PO BOX 650003 M S WT 93 DALLAS TX 75265-0003
1	HYDROGEOLOGIC INC SERDP ESTCP SPT OFC S WALSH 1155 HERNDON PKWY STE 900 HERNDON VA 20170
4	DIRECTOR SANDIA NATIONAL LABS APPLIED MECHANICS DEPT DIV 8241 W KAWAHARA K PERANO D DAWSON P NIELAN PO BOX 969 LIVERMORE CA 94550-0096

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	NASA LANGLEY RSCH CTR AMSRL VS W ELBER MS 266 F BARTLETT JR MS 266 G FARLEY MS 266 HAMPTON VA 23681-0001	1	GRAPHITE MASTERS INC J WILLIS 3815 MEDFORD ST LOS ANGELES CA 90063-1900
1	NASA LANGLEY RSCH CTR T GATES MS 188E HAMPTON VA 23661-3400	1	ADVANCED GLASS FIBER YARNS T COLLINS 281 SPRING RUN LANE STE A DOWNINGTON PA 19335
1	USDOT FEDERAL RAILRD M FATEH RDV 31 WASHINGTON DC 20590	1	COMPOSITE MATERIALS INC D SHORTT 19105 63 AVE NE PO BOX 25 ARLINGTON WA 98223
1	DOT FHWA J SCALZI 400 SEVENTH ST SW 3203 HNG 32 WASHINGTON DC 20590	1	COMPOSITE MATERIALS INC R HOLLAND 11 JEWEL CT ORINDA CA 94563
1	FHWA E MUNLEY 6300 GEORGETOWN PIKE MCLEAN VA 22101	1	COMPOSITE MATERIALS INC C RILEY 14530 S ANSON AVE SANTA FE SPRINGS CA 90670
1	CENTRAL INTLLGNC AGNCY OTI WDAG GT W L WALTMAN PO BOX 1925 WASHINGTON DC 20505	2	COMPOSIX D BLAKE L DIXON 120 O NEILL DR HEBRUN OHIO 43025
1	MARINE CORPS INTLLGNC ACTVTY D KOSITZKE 3300 RUSSELL RD STE 250 QUANTICO VA 22134-5011	4	CYTEC FIBERITE R DUNNE D KOHLI M GILLIO R MAYHEW 1300 REVOLUTION ST HAVRE DE GRACE MD 21078
1	DIRECTOR NATIONAL GRND INTLLGNC CTR IANG TMT 220 SEVENTH ST NE CHARLOTTESVILLE VA 22902-5396	2	SIMULA J COLTMAN R HUYETT 10016 S 51ST ST PHOENIX AZ 85044
1	DIRECTOR DEFENSE INTLLGNC AGNCY TA 5 K CRELLING WASHINGTON DC 20310	1	SIOUX MFG B KRIEL PO BOX 400 FT TOTTEN ND 58335

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	PROTECTION MATERIALS INC M MILLER F CRILLEY 14000 NW 58 CT MIAMI LAKES FL 33014
3	FOSTER MILLER J J GASSNER M ROYLANCE W ZUKAS 195 BEAR HILL RD WALTHAM MA 02354-1196
1	ROM DEVELOPMENT CORP R O MEARA 136 SWINEBURNE ROW BRICK MARKET PLACE NEWPORT RI 02840
2	TEXTRON SYSTEMS T FOLTZ M TREASURE 201 LOWELL ST WILMINGTON MA 08870-2941
1	JPS GLASS L CARTER PO BOX 260 SLATER RD SLATER SC 29683
1	O GARA HESS & EISENHARDT M GILLESPIE 9113 LESANT DR FAIRFIELD OH 45014
2	MILLIKEN RSCH CORP H KUHN M MACLEOD PO BOX 1926 SPARTANBURG SC 29303
1	CONNEAUGHT INDUSTRIES INC J SANTOS PO BOX 1425 COVENTRY RI 02816

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	BATTELLE C R HARGREAVES 505 KING AVE COLUMBUS OH 43201-2681
2	BATTELLE NATICK OPNS J CONNORS B HALPIN 209 W CENTRAL ST STE 302 NATICK MA 01760
1	BATTELLE NW DOE PNNL T HALL MS K231 BATTELLE BLVD RICHLAND WA 99352
3	PACIFIC NORTHWEST LAB M SMITH G VAN ARSDALE R SHIPPELL PO BOX 999 RICHLAND WA 99352
1	ARMTEC DEFENSE PRODUCTS S DYER 85 901 AVE 53 PO BOX 848 COACHELLA CA 92236
2	ADVANCED COMPOSITE MATERIALS CORP P HOOD J RHODES 1525 S BUNCOMBE RD GREER SC 29651-9208
2	GLCC INC J RAY M BRADLEY 103 TRADE ZONE DR STE 26C WEST COLUMBIA SC 29170
2	AMOCO PERFORMANCE PRODUCTS M MICHNO JR J BANISAUKAS 4500 MCGINNIS FERRY RD ALPHARETTA GA 30202-3944

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	SAIC M PALMER 2109 AIR PARK RD S E ALBUQUERQUE NM 87106	1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078
1	SAIC G CHRYSSOMALLIS 3800 W 80TH ST STE 1090 BLOOMINGTON MN 55431	1	CUSTOM ANALYTICAL ENG SYS INC A ALEXANDER 13000 TENSOR LANE NE FLINTSTONE MD 21530
1	AAI CORPORATION T G STASTNY PO BOX 126 HUNT VALLEY MD 21030-0126	2	LORAL VOUGHT SYSTEMS G JACKSON K COOK 1701 W MARSHALL DR GRAND PRAIRIE TX 75051
1	JOHN HEBERT PO BOX 1072 HUNT VALLEY MD 21030-0126	5	AEROJET GEN CORP D PILLASCH T COULTER C FLYNN D RUBAREZUL M GREINER 1100 WEST HOLLYVALE ST AZUSA CA 91702-0296
1	APPLIED COMPOSITES W GRISCH 333 NORTH SIXTH ST ST CHARLES IL 60174		
12	ALLIANT TECHSYSTEMS INC C CANDLAND C AAKHUS R BECKER B SEE N VLAHAKUS R DOHRN S HAGLUND D FISHER W WORRELL R COPENHAFFER M HISSONG D KAMDAR 600 SECOND ST NE HOPKINS MN 55343-8367	3	HEXCEL INC R BOE F POLICELLI J POESCH PO BOX 98 MAGNA UT 84044
		3	HERCULES INC HERCULES PLAZA WILMINGTON DE 19894
		1	BRIGS COMPANY J BACKOFEN 2668 PETERBOROUGH ST HERNDON VA 22071-2443
3	ALLIANT TECHSYSTEMS INC J CONDON E LYNAM J GERHARD WV01 16 STATE RT 956 PO BOX 210 ROCKET CENTER WV 26726-0210	1	ZERNOW TECHNICAL SERVICES L ZERNOW 425 W BONITA AVE STE 208 SAN DIMAS CA 91773

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	OLIN CORPORATION FLINCHBAUGH DIV E STEINER B STEWART PO BOX 127 RED LION PA 17356
1	OLIN CORPORATION L WHITMORE 10101 NINTH ST NORTH ST PETERSBURG FL 33702
5	SIKORSKY AIRCRAFT G JACARUSO T CARSTENSAN B KAY S GARBO MS S330A J ADELMANN 6900 MAIN ST PO BOX 9729 STRATFORD CT 06497-9729
1	GKN AEROSPACE D OLDS 15 STERLING DR WALLINGFORD CT 06492
1	PRATT & WHITNEY D HAMBRICK 400 MAIN ST MS 114 37 EAST HARTFORD CT 06108
1	AEROSPACE CORP G HAWKINS M4 945 2350 E EL SEGUNDO BLVD EL SEGUNDO CA 90245
2	CYTEC FIBERITE M LIN W WEB 1440 N KRAEMER BLVD ANAHEIM CA 92806
1	HEXCEL T BITZER 11711 DUBLIN BLVD DUBLIN CA 94568

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	BOEING R BOHLMANN PO BOX 516 MC 5021322 ST LOUIS MO 63166-0516
2	BOEING DFNSE & SPACE GP W HAMMOND J RUSSELL S 4X55 PO BOX 3707 SEATTLE WA 98124-2207
2	BOEING ROTORCRAFT P MINGURT P HANDEL 800 B PUTNAM BLVD WALLINGFORD PA 19086
1	BOEING DOUGLAS PRODUCTS DIV L J HART SMITH 3855 LAKEWOOD BLVD D800-0019 LONG BEACH CA 90846-0001
1	LOCKHEED MARTIN S REEVE 8650 COBB DR D 73 62 MZ 0648 MARIETTA GA 30063-0648
1	LOCKHEED MARTIN SKUNK WORKS D FORTNEY 1011 LOCKHEED WAY PALMDALE CA 93599-2502
1	LOCKHEED MARTIN R FIELDS 1195 IRWIN CT WINTER SPRINGS FL 32708
1	MATERIALS SCIENCES CORP B W ROSEN 500 OFC CENTER DR STE 250 FT WASHINGTON PA 19034



<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	NORTHROP GRUMMAN CORP ELECTRONIC SENSORS & SYSTEMS DIV E SCHOCH MS V 16 1745A W NURSERY RD LINTHICUM MD 21090	2	GDLS D REES M PASIK PO BOX 2074 WARREN MI 48090-2074
2	NORTHROP GRUMMAN ENVIRONMENTAL PROGRAMS R OSTERMAN A YEN 8900 E WASHINGTON BLVD PICO RIVERA CA 90660	1	GDLS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090
1	UDLP D MARTIN PO BOX 359 SANTA CLARA CA 95052	1	GDLS MUSKEGON OPERATIONS W SOMMERS JR 76 GETTY ST MUSKEGON MI 49442
1	UDLP G THOMAS PO BOX 58123 SANTA CLARA CA 95052	1	GENERAL DYNAMICS AMPHIBIOUS SYS SURVIVABILITY LEAD G WALKER 991 ANNAPOLIS WAY WOODBIDGE VA 22191
2	UDLP R BARRETT MAIL DROP M53 V HORVATICH MAIL DROP M53 328 W BROKAW RD SANTA CLARA CA 95052-0359	5	INST FOR ADVANCED TECH T KIEHNE H FAIR P SULLIVAN W REINECKE I MCNAB 4030 2 W BRAKER LN AUSTIN TX 78759
3	UDLP GROUND SYSTEMS DIVISION M PEDRAZZI MAIL DROP N09 A LEE MAIL DROP N11 M MACLEAN MAIL DROP N06 1205 COLEMAN AVE SANTA CLARA CA 95052	2	CIVIL ENGR RSCH FOUNDATION PRESIDENT H BERNSTEIN R BELLE 1015 15TH ST NW STE 600 WASHINGTON DC 20005
3	UDLP R BRYNSVOLD P JANKE MS 170 T GIOVANETTI MS 236 B VAN WYK MS 389 4800 EAST RIVER RD MINNEAPOLIS MN 55421-1498	1	ARROW TECH ASSO 1233 SHELBURNE RD STE D 8 SOUTH BURLINGTON VT 05403-7700
		1	R EICHELBERGER CONSULTANT 409 W CATHERINE ST BEL AIR MD 21014-3613

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	UCLA MANE DEPT ENGR IV H T HAHN LOS ANGELES CA 90024-1597
2	UNIV OF DAYTON RESEARCH INST R Y KIM A K ROY 300 COLLEGE PARK AVE DAYTON OH 45469-0168
1	MIT P LAGACE 77 MASS AVE CAMBRIDGE MA 01887
1	IIT RESEARCH CENTER D ROSE 201 MILL ST ROME NY 13440-6916
1	GA TECH RSCH INST GA INST OF TCHNLGY P FRIEDERICH ATLANTA GA 30392
1	MICHIGAN ST UNIV MSM DEPT R AVERILL 3515 EB EAST LANSING MI 48824-1226
1	UNIV OF KENTUCKY L PENN 763 ANDERSON HALL LEXINGTON KY 40506-0046
1	UNIV OF WYOMING D ADAMS PO BOX 3295 LARAMIE WY 82071
1	UNIV OF UTAH DEPT OF MECH & INDUSTRIAL ENGR S SWANSON SALT LAKE CITY UT 84112

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	PENN STATE UNIV R MCNITT C BAKIS 212 EARTH ENGR SCIENCES BLDG UNIVERSITY PARK PA 16802
1	PENN STATE UNIV R S ENGEL 245 HAMMOND BLDG UNIVERSITY PARK PA 16801
1	PURDUE UNIV SCHOOL OF AERO & ASTRO C T SUN W LAFAYETTE IN 47907-1282
1	STANFORD UNIV DEPT OF AERONAUTICS & AEROBALLISTICS S TSAI DURANT BLDG STANFORD CA 94305
1	UNIV OF DAYTON J M WHITNEY COLLEGE PARK AVE DAYTON OH 45469-0240
7	UNIV OF DELAWARE CTR FOR COMPOSITE MTRLs J GILLESPIE M SANTARE G PALMESE S YARLAGADDA S ADVANI D HEIDER D KUKICH 201 SPENCER LABORATORY NEWARK DE 19716
1	UNIV OF ILLINOIS AT URBANA CHAMPAIGN NATIONAL CENTER FOR COMPOSITE MATERIALS RESEARCH J ECONOMY 216 TALBOT LABORATORY 104 S WRIGHT ST URBANA IL 61801

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	THE UNIV OF TEXAS AT AUSTIN CTR FOR ELECTROMECHANICS J PRICE A WALLS J KITZMILLER 10100 BURNET RD AUSTIN TX 78758-4497		<u>ABERDEEN PROVING GROUND</u>
		1	US ARMY MATERIEL SYSTEMS ANALYSIS P DIETZ 392 HOPKINS RD AMXSY BTD APG MD 21005-5071
3	VA POLYTECHNICAL INST & STATE UNIV DEPT OF ESM M W HYER K REIFSNIDER R JONES BLACKSBURG VA 24061-0219	1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP AP L APG MD 21005-5066
		108	DIR USARL AMSRL CI AMSRL CI H W STUREK AMSRL CI S A MARK AMSRL CS IO FI M ADAMSON AMSRL SL B J SMITH AMSRL SL BA AMSRL SL BL D BELY R HENRY AMSRL SL BG A YOUNG AMSRL SL I AMSRL WM B A HORST E SCHMIDT AMSRL WM BA W D AMICO F BRANDON AMSRL WM BC P PLOSTINS D LYON J NEWILL S WILKERSON A ZIELINSKI AMSRL WM BD B FORCH R FIFER R PESCE RODRIGUEZ B RICE
1	NORTH CAROLINA STATE UNIV CIVIL ENGINEERING DEPT W RASDORF PO BOX 7908 RALEIGH NC 27696-7908		
1	UNIV OF MARYLAND DEPT OF AEROSPACE ENGNRNG A J VIZZINI COLLEGE PARK MD 20742		
1	DREXEL UNIV A S D WANG 32ND & CHESTNUT ST PHILADELPHIA PA 19104		
1	SOUTHWEST RSCH INST ENGR & MATL SCIENCES DIV J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510		

NO. OF  
COPIES      ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM BE  
C LEVERITT  
D KOOKER  
AMSRL WM BR  
C SHOEMAKER  
J BORNSTEIN  
AMSRL WM M  
D VIECHNICKI  
G HAGNAUER  
J MCCAULEY  
B TANNER  
AMSRL WM MA  
R SHUFORD  
P TOUCHET  
N BECK TAN  
D FLANAGAN  
L GHIORSE  
D HARRIS  
S MCKNIGHT  
P MOY  
S NGYUEN  
P PATTERSON  
G RODRIGUEZ  
A TEETS  
R YIN  
AMSRL WM MB  
B FINK  
J BENDER  
T BLANAS  
T BOGETTI  
R BOSSOLI  
L BURTON  
K BOYD  
S CORNELISON  
P DEHMER  
R DOOLEY  
W DRYSDALE  
G GAZONAS  
S GHIORSE  
D GRANVILLE  
D HOPKINS  
C HOPPEL  
D HENRY  
R KASTE  
M KLUSEWITZ  
M LEADORE  
R LIEB

NO. OF  
COPIES      ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM MB  
E RIGAS  
J SANDS  
D SPAGNUOLO  
W SPURGEON  
J TZENG  
E WETZEL  
A ABRAHAMIAN  
M BERMAN  
A FRYDMAN  
T LI  
W MCINTOSH  
E SZYMANSKI  
AMSRL WM MC  
J BEATTY  
J SWAB  
E CHIN  
J MONTGOMERY  
A WERECZCAK  
J LASALVIA  
J WELLS  
AMSRL WM MD  
W ROY  
S WALSH  
AMSRL WM T  
B BURNS  
AMSRL WM TA  
W GILLICH  
T HAVEL  
J RUNYEON  
M BURKINS  
E HORWATH  
B GOOCH  
W BRUCHEY  
AMSRL WM TC  
R COATES  
AMSRL WM TD  
A DAS GUPTA  
T HADUCH  
T MOYNIHAN  
F GREGORY  
A RAJENDRAN  
M RAFTENBERG  
M BOTELER  
T WEERASOORIYA  
D DANDEKAR  
A DIETRICH

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
--------------------------	---------------------

ABERDEEN PROVING GROUND (CONT)

	AMSRL WM TE
	A NILER
	J POWELL
	AMSRL SS SD
	H WALLACE
	AMSRL SS SE R
	R CHASE
	AMSRL SS SE DS
	R REYZER
	R ATKINSON
	AMSRL SE L
	R WEINRAUB
	J DESMOND
	D WOODBURY

NO. OF  
COPIES      ORGANIZATION

1      LTD  
R MARTIN  
MERL  
TAMWORTH RD  
HERTFORD SG13 7DG  
UK

1      PW LAY  
SMC SCOTLAND  
DERA ROSYTH  
ROSYTH ROYAL DOCKYARD  
DUNFERMLINE FIFE KY 11 2XR  
UK

1      CIVIL AVIATION  
ADMINSTRATION  
T GOTTESMAN  
PO BOX 8  
BEN GURION INTERNL AIRPORT  
LOD 70150 ISRAEL

1      AEROSPATIALE  
S ANDRE  
A BTE CC RTE MD132  
316 ROUTE DE BAYONNE  
TOULOUSE 31060  
FRANCE

1      DAIMLER BENZ AEROSPACE  
J BAUER  
D 81663 MUNCHEN  
MUNICH  
GERMANY

3      DRA FORT HALSTEAD  
P N JONES  
D SCOTT  
M HINTON  
SEVEN OAKS KENT TN 147BP  
UK

1      DEFENSE RESEARCH ESTAB  
VALCARTIER  
F LESAGE  
COURCELETTE QUEBEC COA  
IRO CANADA

NO. OF  
COPIES      ORGANIZATION

2      ROYAL MILITARY COLLEGE OF  
SCIENCE SHRIVENHAM  
D BULMAN  
B LAWTON  
SWINDON WILTS SN6 8LA  
UK

1      SWISS FEDERAL ARMAMENTS  
WKS  
W LANZ  
ALLMENDSTRASSE 86  
3602 THUN  
SWITZERLAND

1      ISRAEL INST OF  
TECHNOLOGY  
S BODNER  
FACULTY OF MECHANICAL ENGR  
HAIFA 3200 ISRAEL

1      DSTO MATERIALS RESEARCH LAB  
NAVAL PLATFORM VULNERABILITY  
SHIP STRUCTURES & MTRLS DIV  
N BURMAN  
PO BOX 50  
ASCOT VALE VICTORIA  
AUSTRALIA 3032

1      ECOLE ROYAL MILITAIRE  
E CELENS  
AVE DE LA RENAISSANCE 30  
1040 BRUXELLE  
BELGIQUE

1      DEF RES ESTABLISHMENT  
VALCARTIER  
A DUPUIS  
2459 BOULEVARD PIE XI NORTH  
VALCARTIER QUEBEC  
CANADA  
PO BOX 8800 COURCELETTE  
GOA IRO QUEBEC CANADA

1      INSTITUT FRANCO ALLEMAND  
DE RECHERCHES DE SANIT LOUIS  
DE M GIRAUD  
5 RUE DU GENERAL CASSAGNOU  
BOITE POSTALE 34  
F 68301 SAINT LOUIS CEDEX  
FRANCE

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	ECOLE POLYTECH J MANSON DMX LTC CH 1015 LAUSANNE SWITZERLAND	1	ERNST MACH INSTITUT EMI A STILP ECKERSTRASSE 4 7800 FREIBURG GERMANY
1	TNO PRINS MAURITS LABORATORY R IJSSELSTEIN LANGE KLEIWEG 137 PO BOX 45 2280 AA RIJSWIJK THE NETHERLANDS	1	TNO DEFENSE RESEARCH I H PASMAN POSTBUS 6006 2600 JA DELFT THE NETHERLANDS
2	FOA NAT L DEFENSE RESEARCH ESTAB DIR DEPT OF WEAPONS & PROTECTION B JANZON R HOLMLIN S 172 90 STOCKHOLM SWEDEN	1	B HIRSCH TACHKEMONY ST 6 NETAMUA 42611 ISRAEL
2	DEFENSE TECH & PROC AGENCY GROUND I CREWTHIER GENERAL HERZOG HAUS 3602 THUN SWITZERLAND	1	DEUTSCHE AEROSPACE AG DYNAMICS SYSTEMS M HELD PO BOX 1340 D 86523 SCHROBENHAUSEN GERMANY
1	MINISTRY OF DEFENCE RAFAEL ARMAMENT DEVELOPMENT AUTH M MAYSELESS PO BOX 2250 HAIFA 31021 ISRAEL		
1	DYNAMEC RESEARCH AB A PERSSON BOX 201 S 15123 SODERTALJE SWEDEN		
1	ERNST MACH INSTITUT EMI DIRECTOR HAUPTSTRASSE 18 79576 WEIL AM RHEIN GERMANY		

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2000	3. REPORT TYPE AND DATES COVERED Final, Jan 98-Jan 99	
4. TITLE AND SUBTITLE On the Application of Genetic Algorithms for Optimization of RTM Process Parameters			5. FUNDING NUMBERS AH42	
6. AUTHOR(S) Bruce K. Fink, Roopesh Mathur,* and Suresh G. Advani*				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WM-MB Aberdeen Proving Ground, MD 21005-5069			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-2317	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES *University of Delaware, Newark, DE 19716				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p>Resin infusion processes are finding increasing applications in the manufacture of composite parts that have geometric and material complexities. In such cases, the placement of gates and vents is nonintuitive and may require expensive repetitive experimentation. Finite element-based resin-flow simulation codes have been successfully used for modeling and analysis of the mold-filling process. Such filling simulations, when coupled with a search algorithm, can also prove useful for optimal design of the filling process. Genetic algorithms (GAs) mimic natural selection and can efficiently "evolve" near-global optimal solutions from a large number of alternative solutions. In this paper, GAs are used to optimize gate and vent locations for the resin-transfer molding (RTM) process in order to minimize fill times and dry-spot formation. A process performance index, or cost function, is defined, which incorporates the fill time and dry-spot formation as primary variables. A part having material and geometric complexities was chosen for a case study. GA and mold-filling simulations were used interactively to search for optimal gate and vent locations to locate near-optimal solutions. The GA was able to find good solutions using less than 1% of simulations of the possible permutations of gates and vents. The case study was also repeated in the presence of racetracking channels. Again, the optimal locations were found by the GA using less than 1% of all possible combinations.</p>				
14. SUBJECT TERMS composite material, genetic algorithm, resin transfer modeling, process optimization			15. NUMBER OF PAGES 51	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	



INTENTIONALLY LEFT BLANK.

## USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2317 (Fink) Date of Report September 2000
2. Date Report Received \_\_\_\_\_
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT  
ADDRESS

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
E-mail Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD  
ADDRESS

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)  
(DO NOT STAPLE)